Recent Results and Future Plans of the MoEDAL Experiment

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EPS-HEP 2019
Ghent, Belgium
On behalf of
MoEDAL Collaboration

July 12, 2019
Magnetic Monopoles: symmetrising Maxwell’s equation

- No magnetic monopole has been seen to date.
- The isolated magnetic charges were not present in Maxwell’s equation.
  - The equations are asymmetric in electric and magnetic charge.
- A magnetic monopole restores the symmetry to Maxwell’s equation

<table>
<thead>
<tr>
<th>Name</th>
<th>Without Magnetic Monopoles</th>
<th>With Magnetic Monopoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss’s law:</td>
<td>$\nabla \cdot \vec{E} = 4\pi \rho_e$</td>
<td>$\nabla \cdot \vec{E} = 4\pi \rho_e$</td>
</tr>
<tr>
<td>Gauss’s law for magnetism:</td>
<td>$\nabla \cdot \vec{B} = 0$</td>
<td>$\nabla \cdot \vec{B} = 4\pi \rho_m$</td>
</tr>
<tr>
<td>Faraday’s law of induction:</td>
<td>$-\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t}$</td>
<td>$-\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} + 4\pi \vec{J}_m$</td>
</tr>
<tr>
<td>Ampère’s law (with Maxwell’s extension)</td>
<td>$\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$</td>
<td>$\nabla \times \vec{B} = \frac{\partial \vec{E}}{\partial t} + 4\pi \vec{J}_e$</td>
</tr>
</tbody>
</table>

Note: the Bivector notation embodies the sign swap, and these four equations can be written as only one equation.

- Symmetrised Maxwell’s equations are invariant under rotation in (E,B) plane.
- Distinction between electric and magnetic charge becomes just definition.
Paul Dirac in 1931 thought of monopoles as the end of an infinitely long and thin solenoid.

Dirac’s quantization condition:

\[ ge = n \left( \frac{\hbar c}{2} \right) \quad \text{or} \quad g = \left( \frac{n}{2\alpha} \right) e, \quad n = 1, 2, 3... \]

where \( g \) is the magnetic charge and \( \alpha = 1/137 \).

- **Single magnetic charge:** \( g_D = 68.5e \).
- **Large coupling constant:** \( \frac{g}{\hbar c} \sim 20 \), perturbative calculation impossible for general case.
- **Monopoles would accelerate along field lines- Lorentz equation:** \( \vec{F} = g(\vec{B} - \vec{v} \times \vec{E}) \).

**Dirac monopole properties**
- Dirac monopole is a point-like particle.
- Spin and mass are not determined by the theory.
MoEDAL is largely passive; made up of three detector systems:

- **NUCLEAR TRACK DETECTOR**
  - Plastic array (~200 sqm)
  - Like a Giant Camera

- **TRAPPING DETECTOR ARRAY**
  - A tonne of Al to trap Highly Ionizing Particles for analysis

- **TIMEPIX Array**, a digital Camera for real time radiation monitoring
MMM-2 and MMM-3 (sides) are newly added with respect to previous MoEDAL analyses. Latest analysis is based on data extracted from all MMMTs. After the exposure, Al bars are passed through SQUID Magnetometer to check the presence of magnetic monopole.
The SQUID Response of MMTs: Monopole search

- Magnetic charges $> 0.5 \ g_D$ can be excluded at high confidence level.
- A threshold of $0.4 \ g_D$ was used to identify potential candidate samples.
- The candidate samples were passed through SQUID a number of times to check if they really contain any monopole.
MoEDAL result with persistent current:

\[ \sqrt{s} = 13 \text{ TeV}, 4.0 \text{ fb}^{-1} \]

Sample number

- Cross-section upper limits as low as 11 fb were set.
- Mass limits in the range of 1500 GeV to 3750 GeV.
- Mass limits are the strongest at a collider experiment.

- Mass limits based on Feynman-like diagrams, where perturbative calculations are impossible due to large $\gamma$-monopole coupling. They only serve to facilitate comparisons.
Beyond Magnetic Monopole Search
Prospect of SUSY searches at the MoEDAL experiment (Sakurai, Felea, Mamuzic, Mavromatos, Mitsou, Pinfold, Ruiz de Austri, AS, Vives, arXiv:1903.11022):

- MoEDAL can be useful for SUSY search, for example $\tilde{g}\tilde{g} \to jj\tilde{\chi}^0_1$, $\tilde{\chi}^0_1 \to \tau^\pm\tilde{\tau}_1$.
- $\tilde{\chi}^0_1$ long-lived despite large mass splitting between $\tilde{\chi}^0_1$ and $\tilde{\tau}_1$: decays in tracker.
- (massive) $\tau^\pm$ produces a kink between $\tilde{\chi}^0_1$ and $\tilde{\tau}_1$ tracks: large impact parameter $d_{xy}$, $d_z$.
- CMS sensitivity suffers because of no pixel hit (long lived neutralino) and too large impact parameter for $\tilde{\tau}$.
- MoEDAL is useful here: can cover long-lifetime region with nominal NTD performance $z/\beta > 5$.

$\tilde{g}$ decay diagram (left) and CMS exclusion with MoEDAL discovery potential requiring 2 signal events for MoEDAL (right).
Future Developments
**CMS beam pipe**

**Beam pipe**
- most directly exposed piece of material of the experiment.
- covers very high magnetic charges, which may be trapped in upstream material before reaching the MoEDAL MMTs.

**Present status**
- first piece of CMS beam pipe tested in 2012 (EPJC72 (2012) 2212): but this was far from the collision point.
- CMS and MoEDAL collaborations signed agreement transferring ownership of the Run-1 CMS beam pipe to MoEDAL.
  - made of beryllium, 6 m long and 4 cm diameter pipe, highly toxic.

**Next steps:**
- cut beam pipes in small pieces at the University of Alberta, Canada.
- Feed into the SQUID at ETH Zurich (Summer 2019)
- perform simulation studies to assess acceptance.
Motivation
- detect fractionally charged particles - $q \geq 10^{-3}e$.
- detect neutrals with very long lifetime.
- anomalously penetrating particles.

The MAPP:
- 2 arrays each with 100 bars ($10 \times 10 \times 100 \text{ cm}^3$) of high yield scintillator.
- Each bar is readout by two low noise PMTs.
- These two sections sandwiched between 3 ToF ($\sigma_t \sim 100\text{ps}$) hodoscopes.

Prototype
- $3 \times 3$ bars ($\sim 30 \times 30 \text{ cm}^2$) $\rightarrow$ roughly 10% of full detector.
Summary and Conclusion:

- Magnetic monopoles continue to excite interest and have been the subject of numerous experimental searches.
- The MoEDAL experiment is one of the key players in the quest.
- Shown the results from MoEDAL experiment with both photon fusion ($\gamma\gamma$) and Drell-Yan (DY) mechanism
  - First instance of exclusion limit set using the $\gamma\gamma$ mechanism at the LHC.
  - Mass limits in the range 1500-3750 GeV were set for magnetic charges up to 5 $g_D$ for monopoles of spin 0, 1/2 and 1 - strongest to date at a collider experiment.
- MoEDAL can also search for (meta)stable electrically-charged massive particles.
- Further detector extensions are in progress.
THANK YOU for your ATTENTION!
• Bonus slides
• Cross-section calculation
Electric-magnetic duality: The monopole enters the field as a matter field in a U(1) gauge theory.

In short:
- Spin 0: Scalar QED
- Spin 1/2: Dirac QED
- Spin 1: Lee-Yang Field Theory

\[ \beta \]-dependent coupling

Milton (arXiv:hep-ex/0602040) derived the electron-monopole scattering cross-section for small scattering angle:

\[ \frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2} \left[ \left( \frac{eg}{c} \right)^2 \right] \frac{1}{(\theta/2)^4} \]

where \( g \) is the magnetic charge of the monopole.

Rutherford scattering formula:

\[ \frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2} \left[ \left( \frac{e_1 e_2}{v_0} \right)^2 \right] \frac{1}{(\theta/2)^4} \]

can be obtained from Milton’s calculation if \( \frac{e_2}{v_0} \to \frac{g}{c} \) or \( e_2 \to \frac{gv_0}{c} = g\beta \).
Introduction of a new magnetic-moment parameter $\kappa$

Spin 1/2
- Such a term appears through spin interactions in minimally $e^\pm - \gamma$ QED coupling
- SM case: $\tilde{\kappa} = \kappa M = 0$ (unitary and renormalisable)

Spin 1
- Such a term appears through the coupling of $W^\pm$ bosons in rotated $SU(2) \times U_Y(1)/U_{em}(1)$.
- SM case: $\kappa = 1$ (unitary, renormalisable and no ghosts or gauge fixing)

- Total cross-sections increase with $\kappa$.
- Kinematic distributions change with $\kappa$.

Perturbative limit:
- There can be a perturbative limit if:
  - very slow monopoles with $\beta \to 0$.
  - $\kappa$ becomes very large, $\kappa \to \infty$.
  - perturbative limit: $g \kappa' \beta^2 < 1$, where $\kappa' = \tilde{\kappa}$ for spin 1/2 and $\kappa' = \kappa$ for spin 1 monopole.
- Cross-section remains finite for both spin 1/2 and 1 at this limit for $\gamma\gamma$, but vanishes for DY.
- **MadGraph** Implementation of Photon Fusion
  - Creating UFO models
  - Validating the models
Photon fusion in **MadGraph**:

- **Drell-Yan** was implemented in **MadGraph** using **Fortran** code setup.
  - This process only had three-particle vertex for all three spins.
  - Used in ATLAS and MoEDAL to interpret the data (up to leading order).
- **Implementing photon fusion process in MadGraph**
  - Spin 0 and 1 monopoles have additional four-particle vertices.
  - **Fortran** code setup is inadequate to describe them.
  - Moved to the new python based UFO models.
  - The new models include both the Drell-Yan and photon fusion method.
UFO models

**UFO: Universal FeynRules Output**

- **FeynRules**: Mathematica package for describing Feynman rules.
- Based on Python objects.
- Requires the model Lagrangian as an input in Mathematica format.
- Model parameters (mass, spin, coupling etc) are kept in a text file.

For $\beta$-dependent coupling, it is introduced as a Fortran form factor.

- Used the definition of $\beta = \sqrt{1 - 4M^2/\hat{s}}$ with $\hat{s} = 2P_1 \cdot P_2$ for LHC collision of quarks, where $P_1$ and $P_2$ are the four momenta of the incoming colliding particles.
- Point to note: $\beta \to 0$ when $\hat{s} \to (2M)^2$.
- The UFO models were validated by comparing the cross-section values coming from them and the theoretical cross-section values for several monopole masses, and all three spins: 0, 1/2 and 1.
Why consider photon fusion?:

The reason:

- Dougall and Wick (arXiv:0706.1042) showed that the $\gamma\gamma \rightarrow mm^+ mm^-$/DY cross section ratio of monopole production is $\sim 4700$ times that of lepton production.

- Drees et.al. (Phys. Rev. D 50, 2335 (1994)) showed that the $\gamma\gamma \rightarrow mm^+ mm^-$ production of leptons is nearly $10^2$ below DY for pp collisions at $\sqrt{s} = 14$ TeV.

- Hence a factor of $\sim 47$ dominance of $\gamma\gamma \rightarrow mm^+ mm^-$ over DY for monopole production (when $\beta \approx 1$)

Figure: Cross-section vs mass plot for photon fusion and DY process. (arXiv:0706.1042)
Latest ATLAS DY result (arXiv:1905.10130)
Acceptance plots for DY:
The mass limits:

<table>
<thead>
<tr>
<th>Process / coupling</th>
<th>Spin</th>
<th>Magnetic charge $[g_D]$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>95% CL mass limits [GeV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DY</td>
<td>0</td>
<td>790</td>
<td>1150</td>
<td>1210</td>
<td>1130</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY</td>
<td>½</td>
<td>1320</td>
<td>1730</td>
<td>1770</td>
<td>1640</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY</td>
<td>1</td>
<td>1400</td>
<td>1840</td>
<td>1950</td>
<td>1910</td>
<td>1800</td>
<td></td>
</tr>
<tr>
<td>DY β-dep.</td>
<td>0</td>
<td>670</td>
<td>1010</td>
<td>1080</td>
<td>1040</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>DY β-dep.</td>
<td>½</td>
<td>1050</td>
<td>1450</td>
<td>1530</td>
<td>1450</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY β-dep.</td>
<td>1</td>
<td>1220</td>
<td>1680</td>
<td>1790</td>
<td>1780</td>
<td>1710</td>
<td></td>
</tr>
<tr>
<td>DY+$\gamma\gamma$</td>
<td>0</td>
<td>2190</td>
<td>2930</td>
<td>3120</td>
<td>3090</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY+$\gamma\gamma$</td>
<td>½</td>
<td>2420</td>
<td>3180</td>
<td>3360</td>
<td>3340</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY+$\gamma\gamma$</td>
<td>1</td>
<td>2920</td>
<td>3620</td>
<td>3750</td>
<td>3740</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY+$\gamma\gamma$ β-dep.</td>
<td>0</td>
<td>1500</td>
<td>2300</td>
<td>2590</td>
<td>2640</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>DY+$\gamma\gamma$ β-dep.</td>
<td>½</td>
<td>1760</td>
<td>2610</td>
<td>2870</td>
<td>2940</td>
<td>2900</td>
<td></td>
</tr>
<tr>
<td>DY+$\gamma\gamma$ β-dep.</td>
<td>1</td>
<td>2120</td>
<td>3010</td>
<td>3270</td>
<td>3300</td>
<td>3270</td>
<td></td>
</tr>
</tbody>
</table>
• Studying sensitivity with different $\beta$ thresholds:
  - $0.1$ ($z/\beta=10$)
  - $0.15$ ($z/\beta\approx 6.7$)
  - $0.2$ ($z/\beta=5$)

MoEDAL can cover long-lifetime region with less-than-nominal NTD performance $z/\beta > 6.7$

Other decay chains studied too, e.g. $\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\pi^+\tilde{\tau}_1$
$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\rightarrow\nu_\tau\tilde{\tau}_1$
ATLAS & CMS limits on LL gluinos

1. Energy deposition (dE/dx) in inner tracker, e.g. Pixel detector
2. Time-of-flight in outer muon system

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

MoEDAL

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummarySummaryPlots/SUSY/

Detector response not fully calibrated for HIPs
Spin 0 monopoles

- Scalar QED.
- monopole obeying U(1)-gauged Klein-Gordon equation.
- $\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + (D^\mu \phi)^\dagger (D_\mu \phi) - M^2 \phi^\dagger \phi$
Spin 1/2 monopole

- Dirac QED.
- Monopole as a spinor field obeying a U(1)-gauged Dirac equation.

\[ \mathcal{L}^{S=1/2} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi} (i \gamma \partial - M) \psi - i \frac{1}{4} g (\beta) \kappa F_{\mu\nu} \bar{\psi} [\gamma^\mu, \gamma^\nu] \psi \]
Spin 1/2 cross-sections

Spin 1/2 monopole production by Photon Fusion ($\beta$ independent, dimensionless $\bar{\kappa}$) $\sqrt{s} = 4$ TeV

Spin 1/2 monopole production by Drell-Yan ($\beta$ independent, dimensionless $\bar{\kappa}$) $\sqrt{s} = 4$ TeV

Spin 1/2 monopole production by Photon Fusion ($\beta$ independent, dimensionless $\bar{\kappa}$)

Monopole mass $M = 1.5$ TeV
Photon energy $E_\gamma = 6M$

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Recent Results and Future Plans of the MoEDAL Experiment
Spin 1 monopoles

- Lee-Yang field theory.
- Monopole as a vector field obeying a U(1)-gauged Klein Gordon equation with a gauge fixing parameter and ghosts.

\[ \mathcal{L}^{S=1} = -\frac{1}{2} \left( \frac{\partial A_\mu}{\partial x_\nu} \right) \left( \frac{\partial A_\nu}{\partial x_\mu} \right) - \frac{1}{2} G_{\mu\nu} G_{\mu\nu} - M^2 W^\dagger_\mu W^\mu - i g(\beta) \kappa F_{\mu\nu} W^\dagger_\mu W^\nu \]

(a) t-channel.
(b) u-channel.

(c) Four-vertex diagram.
Total cross-section of spin 0, 1/2 and 1:

![Graphs showing cross-section as a function of monopole mass for spin 0, 1/2, and 1 with dependence on β.](image)
Theoretical expressions of cross-section:

\[
\sigma_{\gamma\gamma}^{s=0}(\hat{s}) = \frac{4\pi\alpha_g^2}{\hat{s}} \beta \left[ 2 - \beta^2 - \frac{1 - \beta^4}{2\beta} \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right] \tag{1}
\]

\[
\sigma_{\gamma\gamma}^{s=1/2}(\hat{s}) = \frac{4\pi\alpha_g^2}{\hat{s}} \beta \left[ -2 + \beta^2 + \frac{3 - \beta^4}{2\beta} \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right] \tag{2}
\]

\[
\sigma_{\gamma\gamma}^{s=1}(\hat{s}) = \frac{\pi\alpha_g^2}{\hat{s}} \beta \left[ 2 \frac{22 - 9\beta^2 + 3\beta^4}{1 - \beta^2} - 3 \frac{1 - \beta^4}{\beta} \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right] \tag{3}
\]

where

\[
\alpha_g = g^2 \beta^2, \quad \beta = \sqrt{1 - 4M^2/\hat{s}}, \quad \hat{s} = z_1 z_2 s \tag{4}
\]

1. \( g = \sqrt{\frac{137}{4}} = 5.85 \)
2. \( \alpha_g = 34.25 \)
3. form factor = 1.0
4. \( z_1 = z_2 = 1 \)
5. \( \sqrt{s} = 13 \text{ TeV} \)
6. 1 pb = \( 2.5819 \times 10^{-9} \text{ GeV}^{-2} \)
7. \( \hat{s} = 13 \times 13 \text{ TeV}^2 \)
LHC Phenomenology
MadGraph settings for kinematic distribution plots:

- Kinematic distribution plots: Comparison between photon fusion and DY production mechanism, $\beta$-dependent coupling.
- Simulation setup
  - proton-proton collision at 13 TeV center of mass energy.
  - Monopole mass 1500 GeV.
  - magnetic charge of monopole: $1 \, g_D$.
  - For photon fusion, LUXqed is used as the PDF.
  - For DY, NNLOPDF23 is used as the PDF.
Spin 0 monopoles, charge 1 $g_D$, monopole mass 1500 GeV

- For spin 0 monopoles, DY kinetic energy distribution is similar to the $\gamma\gamma$.

- $\eta$ distributions are different-DY events are more centrally produced.
Validation of the UFO models
Cross-section for $\gamma \gamma \rightarrow mm^+ mm^-$, $\beta$-independent coupling, spin 0 monopole, charge 1 $g_D$

- No PDF used in MadGraph to compare with the theoretical value.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$\sigma$ (pb) $\gamma \gamma \rightarrow mm^+ mm^-$ (UFO model)</th>
<th>$\sigma$ (pb) $\gamma \gamma \rightarrow mm^+ mm^-$ (Theory values)</th>
<th>Ratio UFO model/Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000.0</td>
<td>$1.518 \times 10^4$</td>
<td>$1.5039 \times 10^4$</td>
<td>1.009</td>
</tr>
<tr>
<td>2000.0</td>
<td>$1.202 \times 10^4$</td>
<td>$1.1945 \times 10^4$</td>
<td>1.006</td>
</tr>
<tr>
<td>3000.0</td>
<td>9218</td>
<td>9108.09</td>
<td>1.012</td>
</tr>
<tr>
<td>4000.0</td>
<td>7366</td>
<td>7218.79</td>
<td>1.020</td>
</tr>
<tr>
<td>5000.0</td>
<td>6558</td>
<td>6519.68</td>
<td>1.006</td>
</tr>
<tr>
<td>6000.0</td>
<td>5378</td>
<td>5325.76</td>
<td>1.010</td>
</tr>
</tbody>
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<th>$\sigma$ (pb) $\gamma \gamma \rightarrow mm^+ mm^-$ (Theory values)</th>
<th>Ratio UFO model/Theory</th>
<th>$\beta$ $\beta$-dep/$\beta$-ind (UFO model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>$1.4493 \times 10^4$</td>
<td>$1.4336 \times 10^4$</td>
<td>0.99</td>
<td>0.9881</td>
</tr>
<tr>
<td>2000</td>
<td>$9.851 \times 10^3$</td>
<td>$9.791 \times 10^3$</td>
<td>1.006</td>
<td>0.9515 (\sim 0.9515)</td>
</tr>
<tr>
<td>3000</td>
<td>$5.685 \times 10^3$</td>
<td>$5.640 \times 10^3$</td>
<td>1.007</td>
<td>0.8871 (\sim 0.8871)</td>
</tr>
<tr>
<td>4000</td>
<td>2847</td>
<td>2810.5</td>
<td>1.013</td>
<td>0.7882 (\sim 0.7882)</td>
</tr>
<tr>
<td>5000</td>
<td>1094</td>
<td>1087</td>
<td>1.006</td>
<td>0.639 (\sim 0.639)</td>
</tr>
<tr>
<td>6000</td>
<td>117.8</td>
<td>116.53</td>
<td>1.011</td>
<td>0.3846 (\sim 0.3846)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9547 (\sim 0.9881)</td>
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<td></td>
<td>0.8196 (\sim 0.9515)</td>
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<td></td>
<td></td>
<td></td>
<td>0.6167 (\sim 0.8871)</td>
</tr>
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<td></td>
<td></td>
<td>0.3866 (\sim 0.7882)</td>
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<td>0.1658 (\sim 0.639)</td>
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<td></td>
<td></td>
<td>0.022 (\sim 0.3846)</td>
</tr>
</tbody>
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Cross-section for $\gamma\gamma \rightarrow mm^+mm^-$, $\beta$-independent coupling, spin 1/2 monopole, charge 1 $g_D$

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<th>Ratio UFO model/Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>$1.431 \times 10^5$</td>
<td>$1.425 \times 10^5$</td>
<td>1.004</td>
</tr>
<tr>
<td>2000</td>
<td>$1.018 \times 10^5$</td>
<td>$1.007 \times 10^5$</td>
<td>1.010</td>
</tr>
<tr>
<td>3000</td>
<td>$7.755 \times 10^4$</td>
<td>$7.679 \times 10^4$</td>
<td>1.010</td>
</tr>
<tr>
<td>4000</td>
<td>$5.830 \times 10^4$</td>
<td>$5.7404 \times 10^4$</td>
<td>1.016</td>
</tr>
<tr>
<td>5000</td>
<td>$3.817 \times 10^4$</td>
<td>$3.797 \times 10^4$</td>
<td>1.005</td>
</tr>
<tr>
<td>6000</td>
<td>$1.691 \times 10^4$</td>
<td>$1.6705 \times 10^4$</td>
<td>1.012</td>
</tr>
</tbody>
</table>
Cross-section for $\gamma \gamma \rightarrow mm^+ mm^-$, $\beta$-dependent coupling, spin 1/2 monopole, charge 1 $g_D$

- No PDF used in MadGraph to compare with the theoretical value.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$\sigma$ (pb) $\gamma \gamma \rightarrow mm^+ mm^-$ (UFO model)</th>
<th>$\sigma$ (pb) $\gamma \gamma \rightarrow mm^+ mm^-$ (Theory values)</th>
<th>Ratio UFO model/Theory</th>
<th>$\beta$ $\beta$-dep/$\beta$-ind (UFO model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>$1.364 \times 10^5$</td>
<td>$1.358 \times 10^5$</td>
<td>1.004</td>
<td>0.9881</td>
</tr>
<tr>
<td>2000</td>
<td>$8.341 \times 10^4$</td>
<td>$8.2551 \times 10^4$</td>
<td>1.010</td>
<td>0.9515</td>
</tr>
<tr>
<td>3000</td>
<td>$4.803 \times 10^4$</td>
<td>$4.7554 \times 10^4$</td>
<td>1.010</td>
<td>0.8871</td>
</tr>
<tr>
<td>4000</td>
<td>$2.251 \times 10^4$</td>
<td>$2.2156 \times 10^4$</td>
<td>1.012</td>
<td>0.7882</td>
</tr>
<tr>
<td>5000</td>
<td>6362</td>
<td>6331</td>
<td>1.005</td>
<td>0.639</td>
</tr>
<tr>
<td>6000</td>
<td>370</td>
<td>365.5</td>
<td>1.012</td>
<td>0.3846</td>
</tr>
</tbody>
</table>

(IFIC)
Cross-section for $\gamma\gamma \rightarrow mm^+mm^-$, $\beta$-independent coupling, spin 1 monopole, charge 1 $g_D$

- No PDF used in MadGraph to compare with the theoretical value.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$\sigma$ (pb) $\gamma\gamma \rightarrow mm^+mm^-$ (UFO model)</th>
<th>$\sigma$ (pb) $\gamma\gamma \rightarrow mm^+mm^-$ (Theory values)</th>
<th>Ratio UFO model/Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>$1.131 \times 10^7$</td>
<td>$1.131 \times 10^7$</td>
<td>1.000</td>
</tr>
<tr>
<td>2000</td>
<td>$2.765 \times 10^6$</td>
<td>$2.747 \times 10^6$</td>
<td>1.007</td>
</tr>
<tr>
<td>3000</td>
<td>$1.164 \times 10^6$</td>
<td>$1.151 \times 10^6$</td>
<td>1.011</td>
</tr>
<tr>
<td>4000</td>
<td>$5.879 \times 10^5$</td>
<td>$5.835 \times 10^5$</td>
<td>1.008</td>
</tr>
<tr>
<td>5000</td>
<td>$3.161 \times 10^5$</td>
<td>$3.109 \times 10^5$</td>
<td>1.017</td>
</tr>
<tr>
<td>6000</td>
<td>$1.39 \times 10^5$</td>
<td>$1.378 \times 10^5$</td>
<td>1.009</td>
</tr>
</tbody>
</table>
Cross-section for $\gamma\gamma \rightarrow mm^+ mm^-$, $\beta$-dependent coupling, spin 1 monopole, charge 1 $g_D$

- No PDF used in **MadGraph** to compare with the theoretical value.

<table>
<thead>
<tr>
<th>Mass (GeV)</th>
<th>$\gamma\gamma \rightarrow mm^+ mm^-$ ($\sigma$ (pb)) (UFO model)</th>
<th>$\gamma\gamma \rightarrow mm^+ mm^-$ ($\sigma$ (pb)) (Theory values)</th>
<th>Ratio UFO model/Theory</th>
<th>$\beta$</th>
<th>Ratio $\beta$-dep/$\beta$-ind (UFO model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>$1.078 \times 10^7$</td>
<td>$1.0781 \times 10^7$</td>
<td>0.999</td>
<td>0.9881</td>
<td>0.9531 ($\sim 0.9881^4$)</td>
</tr>
<tr>
<td>2000</td>
<td>$2.277 \times 10^6$</td>
<td>$2.2520 \times 10^6$</td>
<td>1.011</td>
<td>0.9515</td>
<td>0.8235 ($\sim 0.9515^4$)</td>
</tr>
<tr>
<td>3000</td>
<td>$7.214 \times 10^5$</td>
<td>$7.1290 \times 10^5$</td>
<td>1.012</td>
<td>0.8871</td>
<td>0.6198 ($\sim 0.8871^4$)</td>
</tr>
<tr>
<td>4000</td>
<td>$2.275 \times 10^5$</td>
<td>$2.2523 \times 10^5$</td>
<td>1.010</td>
<td>0.7882</td>
<td>0.3870 ($\sim 0.7882^4$)</td>
</tr>
<tr>
<td>5000</td>
<td>$5.256 \times 10^4$</td>
<td>$5.1833 \times 10^4$</td>
<td>1.014</td>
<td>0.639</td>
<td>0.1663 ($\sim 0.639^4$)</td>
</tr>
<tr>
<td>6000</td>
<td>$3.034 \times 10^3$</td>
<td>$3.014 \times 10^3$</td>
<td>1.007</td>
<td>0.3846</td>
<td>0.0218 ($\sim 0.3846^4$)</td>
</tr>
</tbody>
</table>
Milton (arXiv:hep-ex/0602040) derived the electron-monopole scattering cross-section for small scattering angle: 
\[ \frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2} \left[ \left( \frac{eg}{c} \right)^2 \right] \frac{1}{(\theta/2)^4} \]
where \( g \) is the magnetic charge of the monopole.

Rutherford scattering formula: 
\[ \frac{d\sigma}{d\Omega} = \frac{1}{(2\mu v_0)^2} \left[ \left( \frac{e_1 e_2}{v_0} \right)^2 \right] \frac{1}{(\theta/2)^4} \]
can be obtained from Milton’s calculation if \( \frac{e_2}{v_0} \rightarrow \frac{g}{c} \) or \( e_2 \rightarrow \frac{g v_0}{c} = g\beta \).

This leads to \( \alpha = \frac{e^2}{\hbar c} \rightarrow \alpha_m = \frac{(g\beta)^2}{\hbar c} \).

The Lorentz Force law: 
\[ \vec{F} = e\vec{E} + e\beta \vec{c} \times \vec{B} \];
even though the interaction with the magnetic field depends on \( \beta \), the QED coupling depends only on \( e \): 
\[ \alpha = \frac{e^2}{\hbar c} \].

Force on the monopole: 
\[ \vec{F} = g\vec{B} - g\beta \vec{c} \times \vec{E} \].

This does not necessarily imply that the photon-monopole coupling should be \( \beta \)-dependent.
A more direct approach to inferring the magnetometer response to a monopole is to use a long solenoid since the magnetic field from one end of a “semi-infinite” solenoid acts just like a monopole.
The SQUID Magnetometer:

Laboratory of Natural Magnetism, ETH Zurich
Magnetically shielded room
DC SQUID magnetometer
MoEDAL’s sensitivity:

<table>
<thead>
<tr>
<th>detector</th>
<th>energy threshold</th>
<th>angular coverage</th>
<th>luminosity</th>
<th>robust against timing</th>
<th>robust efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>medium</td>
<td>central</td>
<td>high</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>CMS</td>
<td>relatively low</td>
<td>central</td>
<td>high</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>ALICE</td>
<td>very low</td>
<td>very central</td>
<td>low</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>LHCb</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>MoEDAL</td>
<td>low</td>
<td>full</td>
<td>medium</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

Cross-section limits for magnetic (left) and electric charge (right) [arXiv:1112.2999v2 [hep-ph]].

MoEDAL compliments the physics reach of the existing LHC experiments.
The MoEDAL Sub-detector Resolution:

**NTDs**
- Tracking resolution: 10 mm/pit (∼10 pits).
- Pointing resolution to the interaction point: ∼1 cm.
- Charge resolution: 0.1e.

**Trapping Detector:**
- Magnetic charge resolution: < 0.1 $g_D$.

**TimePix chips**
- Pixel size $55 \times 55$ mm$^2$.
- Silicon thickness: 300 µm.